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by Henry W. Brandhorst, Jr., and Adolph E. Spakowski

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Cleveland, Ohio

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SUMMARY

A large film solar cell array was built to explore the construction problems associated with the assembly of flexible, large-area solar cells. The array contains 378 cells, is 7 feet (2.13 m) long and 3.35 feet (1.02 m) wide, and weighs 1.76 pounds (0.8 kg). The array is extended vertically from a storage drum by self-extending booms. Provision is also made for complete retraction of the array and booms. In air mass 1 sunlight at 25° C the array output was 43.8 watts per pound (96.5 W/kg) of cells. The overall array had an efficiency of 3.55 percent and a cell packing factor of 0.94. Efficiencies of cells used in the array ranged between 3.0 and 5.5 percent, and no cell selection was made during assembly. Cell series connections had a resistance of less than 0.5 milliohm and a tensile strength to rupture of 70 pounds (31.75 kg). The demonstration model has been extended and retracted over 500 times with no damage to either cells or connections.

INTRODUCTION

In late 1966, a demonstration model of an active cadmium sulfide thin-film solar cell array was assembled at the Lewis Research Center. The purpose of this work was not to construct a flight or prototype unit but to construct for the first time a large film solar cell array in order to explore the construction problems associated with the assembly of large-area, thin-film solar cells. This report describes the construction and performance of the array.

SOLAR CELL ARRAY

The 3- by 3-inch (7.62- by 7.62-cm) cadmium sulfide thin-film solar cells used in the array were manufactured by the Clevite Corporation during 1965 and 1966 (ref. 1). The array includes 378 cells, of which 376 are encapsulated in 0.001-inch (0.0025-cm)

Mylar, while the other two use 0.001-inch (0.0025-cm) Kapton. A total of 13 cells have 0.001-inch (0.0025-cm) copper substrates; the rest have 0.001-inch (0.0025-cm) Kapton substrates which have been covered with a conductive coating. All grids are gold-plated copper and have been cemented to the surface of the cell with a conductive epoxy resin. All cover plastics have been cemented to the cell with epoxy.

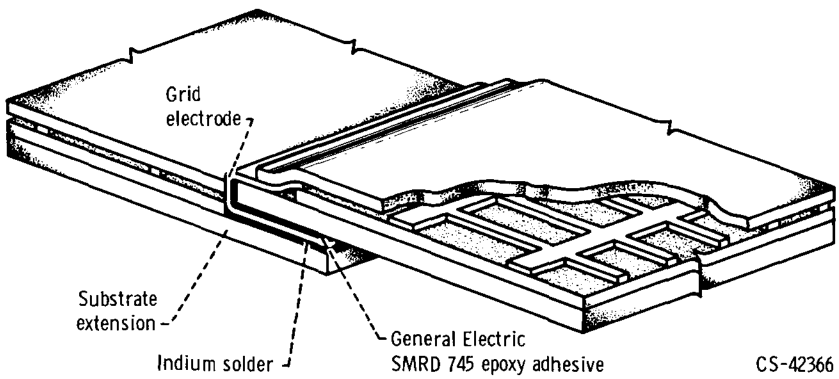

Figure 1. - Detail of series connections in cadmium sulfide thin-film solar cell array.

Details of the series connections are shown in figure 1. A thin film of indium was applied to both the substrate extension and the top of the grid electrode at a temperature of 160° C prior to assembly. The molten indium was burnished at this temperature until a minimum amount remained. The grid electrode was then folded under and placed over the substrate extension. When the two cells were properly alined, the junction was heated and the cells soldered together. Contact resistance of this joint was approximately 0.5 milliohm. Mechanical strength was obtained by applying a layer of General Electric SMRD 745 epoxy adhesive to the back of the top cell. The joint was held together under pressure between two Teflon sheets and cured for 16 hours at 63° C. The resulting joint was exceedingly strong. Several joined cells were tested to destruction in an Instron tensile machine operated at a constant loading rate, and a pull of at least 70 pounds (31.75 kg) was required to separate the cells. At no time during the tests did the joint ever separate. The fact that all cell fractures occurred in the substrate of the lower cell confirmed our belief that no additional substrate is required for mounting these cells in large arrays. Two minor problems arose during assembly of the series strings. The first was caused by size differences, which led to 20 cell series strings varying in length up to 1 inch (2.54 cm). Secondly, alinement problems were encountered because of grids that were slightly crooked. Both problems can be resolved through better quality control in production of the cells.

Series strings were connected in parallel with either 1-inch- (2.54-cm) wide Kapton or Teflon FEP tape. Some difficulty was encountered when the tape was stretched slightly during attachment. It would then shrink; this shrinkage was accompanied by a slight bowing of the cells. No tensile tests were made on this joint.

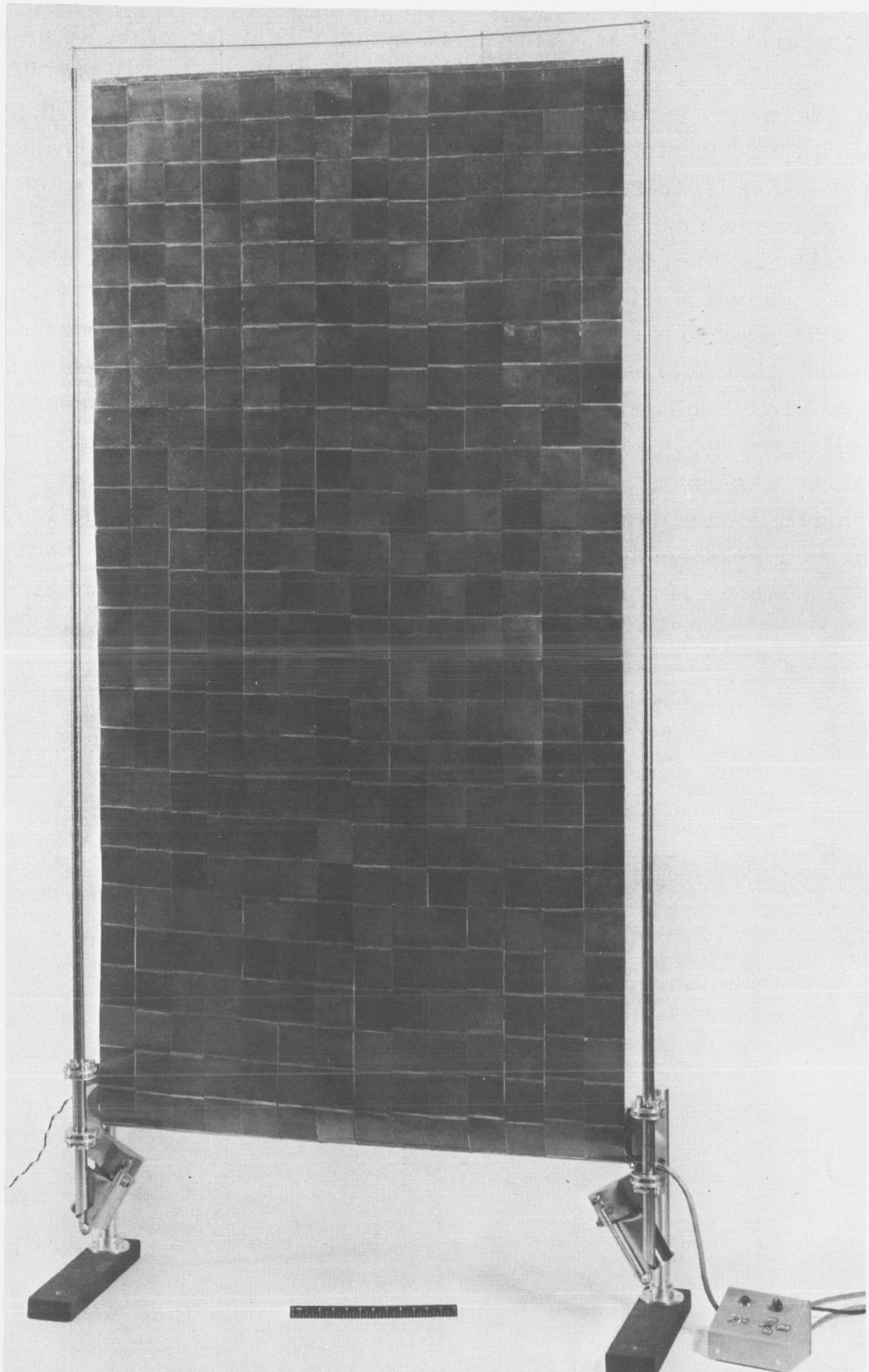

Figure 2. - Solar-cell array in extended position.

The total array shown in figure 2 is 7 feet (2.13 m) long and 3.35 feet (1.02 m) wide and covers an area of 23.4 square feet (2.17 sq m). The weight of the array is 1.76 pounds (0.8 kg) of which 1.55 pounds (0.7 kg) are due to the cells. Of the 378 cells in the array, 280 or approximately 75 percent are connected electrically. The power requirements for a demonstration given during the 1966 Inspection of Lewis Research Center were met by 280 cells; therefore, the remaining cells were added solely to test the extension of the erection mechanism.

The total active area is 17.2 square feet (1.6 sq m). Again, the width is 3.35 feet (1.02 m), but the length is 5.17 feet (1.58 m). Figure 3 shows how the array was electrically divided into two parts, each consisting of seven parallel strings containing 20 series-connected cells each. The two parts were then joined in series to give the desired open-circuit voltage. The parallel connections were made at the end of the strings with copper bus. No redundant joints were made between cells. Extreme care was exercised in soldering to each substrate extension, as too high a temperature would remove the metalized surface. Here again, indium solder was used, and the copper bus was tinned prior to assembly. The series connection was made across the top of the array and then a layer of aluminum tape was added for appearance and to give additional

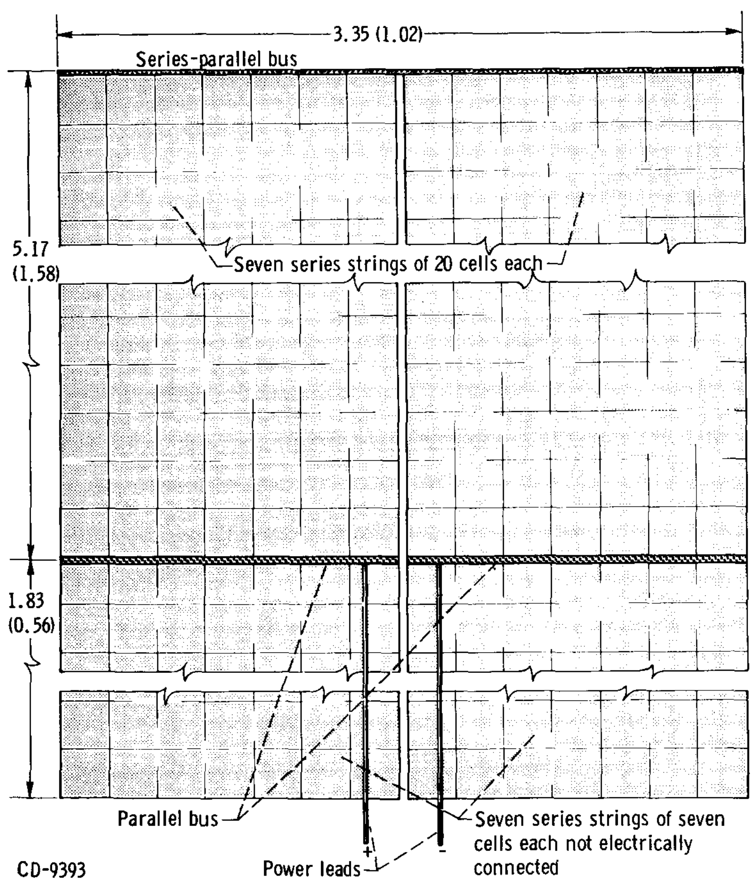

Figure 3. - Electrical connections of array. (All dimensions in feet (m).)

strength. The remaining 98 cells were assembled into a 14 by 7 matrix and attached directly to the bottom of the active array.

ERECTION MECHANISM

The erection mechanism shown in figure 4 was developed by the Hunter Spring Division of AMETEK, Incorporated, and is based on two self-extending booms of spirally wound stainless-steel strips called STACERS (acronym for Spiral Tube and Actuator for Controlled Extension and Retraction). When released, the prestressed 4-inch- (10.16-cm) wide strip extends itself into a spiral tube. Between the two STACER units is a 4-inch- (10.16-cm) diameter drum on which the solar cells are wound. This drum also contains a mechanical servocontrol system which ensures that both booms extend and retract at the same rate. Furthermore, the servocontrol provides a shutoff under three limit conditions:

(1) If the booms are fully retracted

(2) If the booms are fully extended to any set length up to 10 feet (3.05 m)

(3) If a displacement of more than 1/2 inch (1.27 cm) has occurred in the length of the booms on either extension or retraction

The servocontrol system operates two electric motors located inside the spools which store the strips. In operation, the motors are operated independently to brake the faster tube. At full load, the motors draw 1 ampere of current and operate over a dc

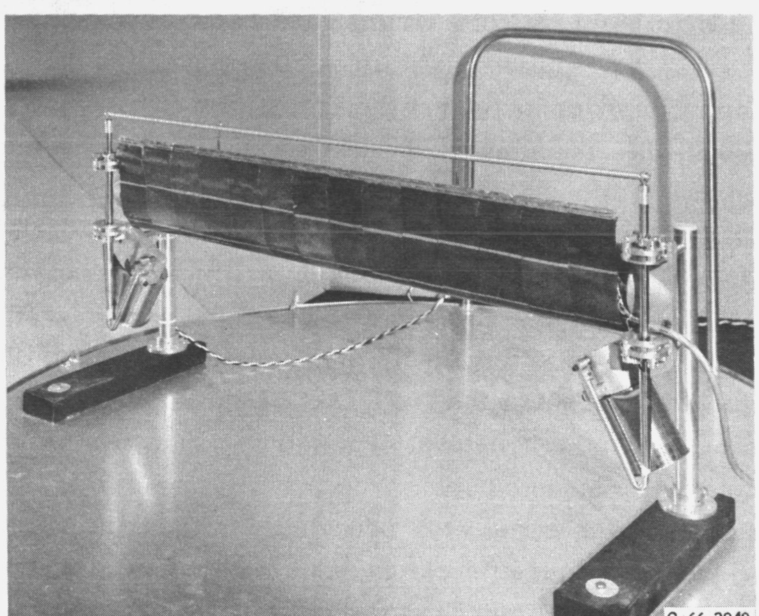

Figure 4. - Solar-cell array in stored position.

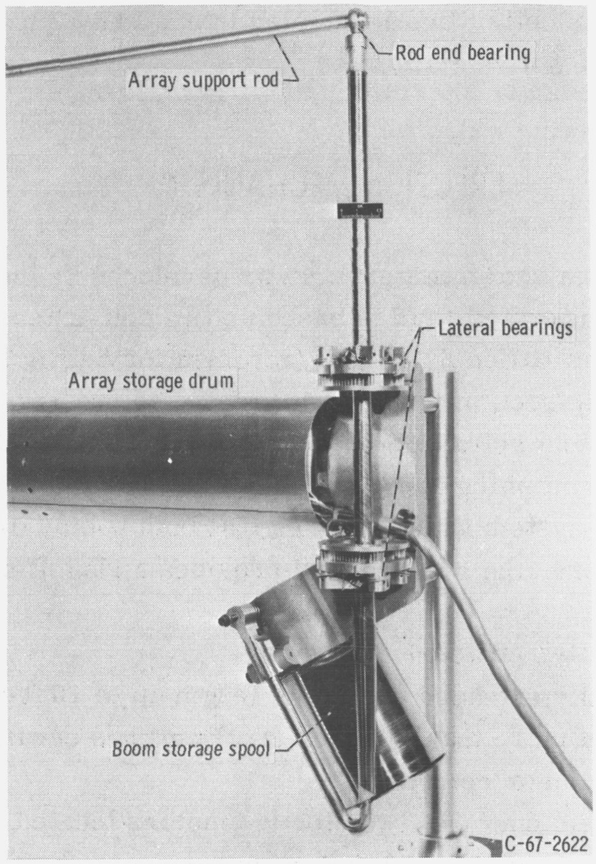

Figure 5. - Close-up of STACER unit and solar-cell storage drum.

voltage range from 12 to 24 volts. In practice, the dc voltage is kept between 12 to 15 volts to provide a controllable rate of extension and retraction. Under these conditions, extension to 7 feet (2.13 m) requires about 15 to 20 seconds and retraction, about the same amount of time. In order to retract the array, the motors are reversed and the tubes are rewound onto the spools under the control of the servosystem.

A closeup photograph of one STACER unit is shown in figure 5. The spiral tube extends with an overlap of about 3 inches (7.62 cm) of the 4-inch (10.16-cm) strip. The tube rotates upon extension, and therefore each spiral tube tip contains a rod end bearing supported by a rolling element bearing. Each STACER is equipped with a pair of automatic centering lateral bearings to maintain precise alinement and to provide lateral support. The winding directions of the two STACER units are opposite to each other to minimize twisting and maintain structural symmetry. Upon retraction, the storage drum is rewound by an internally mounted spring.

The power leads from the array were brought down the back of the inactive segment to the storage drum. Power takeoff from the rotating drum was accomplished by soldering the power leads to two beryllium-copper strip springs inside the drum, which were attached to, but insulated from, the central nonrotating axis. The bottom edge of the inactive array was taped directly to the storage drum. The top of the array was attached to the rod connecting the two STACERS. A 1/4-inch- (0.63-cm) diameter aluminum rod was attached behind the top edge of the array with Kapton tape. This rod was then attached to the STACER connecting rod with two springs. This method of assembly was entirely satisfactory.

RESULTS

Table I details the parameters of the active portion of the array. In air mass 1 (AM 1) sunlight at 100 milliwatts per square centimeter, the open-circuit voltage was

TABLE I. - PARAMETERS OF CADMIUM SULFIDE THIN-FILM

SOLAR-CELL ARRAY

	Active area	Total area
Area, sq ft (sq m)	17.2 (1.6)	23.4 (2.17)
Size, ft (m)	5.17 by 3.35 (1.58 by 1.02)	7.0 by 3.35 (2.13 by 1.02)
Number of cells	280	378
Total weight, lb (kg)	1.30 (0.59)	1.76 (0.8)
Cell weight, lb (kg)	1.15 (0.52)	1.55 (0.7)
Open-circuit voltage,[a] V	18.0	---------
Short-circuit current,[a] A	5.2	---------
Maximum power,[a] W	57	---------
Power per unit area, W/sq ft (W/sq m)	3.3 (35.6)	---------
Power per unit cell weight, W/lb (W/kg)	43.8 (96.5)	---------
Efficiency, percent	3.55	---------
Packing factor	0.94	0.94

[a]At 100 mW/sq cm of Earth sunlight and 25° C.

18 volts, the short-circuit current was 5.2 amperes, and the maximum power was 57 watts. Solar intensity was determined with an uncollimated cadmium sulfide thin-film standard cell which had been calibrated at air mass 0 (AM 0) by the airplane technique (ref. 2). Air mass 1 calibration was determined from the known ratio AM 0/AM 1 $\cong$ 1.2. From the value of 57 watts for the active array, 3.3 watts per square foot (35.6 W/sq m) or 43.8 watts per pound (96.5 W/kg) of cells is obtained. The overall array efficiency is 3.55 percent, which is good considering that the average efficiency of the cells in the array was 3.9 percent and no cell selection was made in the assembly. Minimum cell efficiency was 3.0 percent, while the best efficiency was 5.5 percent. If proper cell selection had been made, the maximum array efficiency would have been slightly less than 3.9 percent. The ratio of cell active area to total array area (packing factor) is 0.94.

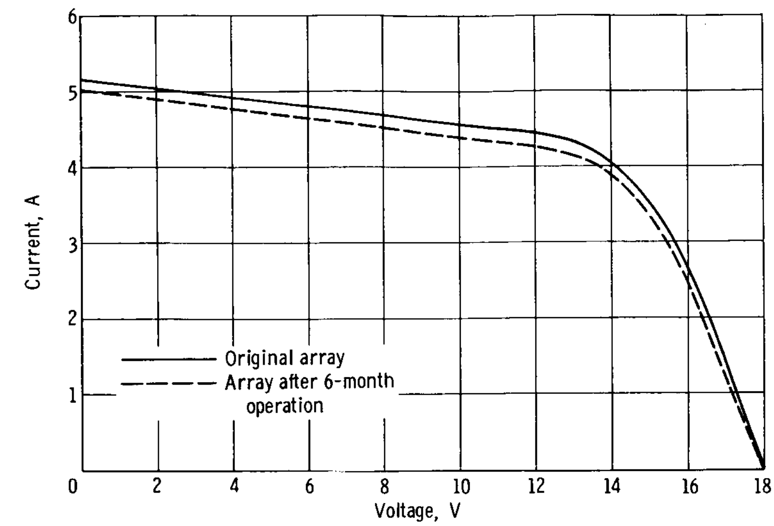

Figure 6. - Characteristic curve of cadmium sulfide solar cell array.

The array was assembled in September 1966 and was extended and retracted more than 500 times in the following 6 months with no damage to grids or connections. In this period, the power output decreased 2 to 3 percent from the initial condition as shown in figure 6. This loss was caused solely by damage which had been sustained by the cells through extremely rough handling. Six cells were torn and at least five other cells had holes completely through them but were still functioning. Several cells ceased to function, but in no case was an open circuit observed. This is consistent with our experience that all modes of failure observed lead to shorted units which will not greatly affect the overall output. No open-circuit condition has ever been observed. The array was stored under ambient room conditions during its lifetime.

An unusual property of the array is its capability for producing audible sounds. Short-circuiting the sunlit array produced an easily heard click which was repeated when the circuit was broken. This may be due to the piezoelectric effect in cadmium sulfide.

It is interesting to use the information developed in this work to estimate array performance in space. The array packing factor was 0.94, and the weight increase in assembly was 13 percent. According to the data of reference 3, individual cells at 50° C in space sunlight at 1 astronomical unit may be expected to be 0.065 pound per square foot (0.318 kg/sq m) and 220 square feet per kilowatt (20.4 sq m/kW). An array should then be 0.074 pound per square foot (0.36 kg/sq m) and 234 square feet per kilowatt (21.7 sq m/kW). If a 20 watt per pound (44.1 W/kg) power system (array plus extension mechanism) is desired, it follows that the extension mechanism must weigh no more than 0.141 pound per square foot (0.69 kg/sq m), or 33 pounds (15 kg) for a 1-kilowatt, 234-square-foot (21.7-sq-m) array. Although the weight of the mechanism used in this work exceeds this figure, it appears possible to build one with this weight or less.

CONCLUSIONS

It has been proved possible to assemble thin-film solar cells into a durable and flexible array. The packing factor of the array was 0.94, and the weight was 13 percent greater than the individual cell weights. The array was strong enough to be self-supporting under tension, eliminating the need for a supporting substrate. It appears that a 20 watt per pound (44.1 W/kg) power system (array plus extension mechanism) may be feasible.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 28, 1967,
120-33-01-02-22.

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